THE FRESHWATER TERTIARY FORMATIONS OF THE ROCKY MOUNTAIN REGION.

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CONTENTS.

1. *Piedmont Depositories of Mountain Waste.* — Extensive plains stretch forward from the base of many mountain ranges. They are formed of the waste brought from the valleys in the mountains by the streams that have for ages drained them. Sometimes the plains are open and slope gently to the seashore, as in northern India and northern Italy; sometimes they occupy a basin drained through a gap in one of its enclosing ranges, as in Hungary and California; sometimes they fill the floors of interior continental basins from which no river escapes to the sea, as in Utah and Nevada, Persia and Central Asia. Although Piedmont fluviatile plains are familiar geographical features, their genetic association with mountains is seldom stated explicitly. It is seldom that sufficient importance is given to the complimentary relation in which the plains stand to the mountain valleys whence their materials have been derived, even though some emphasis may be allowed to the fact that the

form of all vigorous mountains is much more due to the carving of valleys in their uplifted mass than to irregularities in their initial form. The habit of regarding rivers as destructive agents, except near their mouths where they may build deltas in bodies of standing water, seems to have retarded the recognition of the importance of rivers as constructive agents. It is perhaps for this reason that the first suggestion made as to the origin of piedmont plains generally ascribes them to deposition in the sea or in lakes. It only after closer study has been given to their composition, structure, and fossils, as well as to the activities of aggrading rivers, that the prevailing fluviatile origin of most piedmont plains has been recognized. Instead of having been built up from the floor of the sea or of a lake basin, fluviatile plains have frequently accumulated where a slow depression of the land — perhaps an isostatic movement, or a compensation for a slow upheaval of the adjacent mountains — has given them appropriate location. The thickness of piedmont plains on continental margins, as in northern India, may then be much greater than the height of their surface above sea level. The laterally confluent fans of which these plains are built, each fan heading at the mouth of a mountain valley, is good evidence of their origin in the subaerial deposits of aggrading rivers.

Many piedmont plains are to-day slightly dissected, especially near the mountain base, by the rivers that formerly built them up, as in northern India. Others are more strongly dissected, as in the group of great fans at the base of the Pyrenees in southwestern France. Some are tilted and deformed, being thus added as marginal strata to the older mountains from which their materials were derived ; the marginal ridges to which the Righi belongs at the northern base of the Swiss Alps, and the Siwalik range at the base of the Himalayas in northern India are composed of strata of this kind. Yet common as are existing piedmont fluviatile plains, either of interior or exterior drainage, they have not been frequently recognized among geological formations. Their prevailing absence from the geological column may be objective or subjective ; due on the one hand to their real absence in past geological ages ; due on the other hand to the interpretation of fluviatile deposits as formations of non-fluviatile origin.

One reason why the fluviatile deposits of piedmont plains are not more generally recognized in their true relations is that they have no common English name. If their flatter parts are described simply as plains, they are not sufficiently distinguished from plains of other kinds. If their steeper parts are described as slopes, they may be confused with the body of the mountains from which they are derived. The want of an appro-

priate general name for the aggraded floors of interior continental basins is also unfortunate; for several of their features are peculiar to themselves and all are highly specialized and well correlated.

2. *The Various Origins of Stratified Deposits.* — Let us look now at the problem of fluviatile deposits from the other side. A century ago, it was the habit of geologists to regard all stratified deposits as of marine origin. About half a century ago, certain stratified deposits in which no marine fossils were found came to be regarded as of lacustrine origin. In still more recent years, the importance of fluviatile, æolian, and other strictly subaerial agencies in the formation of extensive deposits has been recognized; yet it is still almost habitual to attribute extensive bodies of stratified deposits to a source in bodies of standing water, without a sufficient consideration of other possible origins. It is therefore the intention of this paper to suggest a revision of certain so-called lacustrine deposits, in view of the possibility that they may have been at least in part formed by great rivers, by small streams, or even by the wash and creep of a subarid climate, and that lakes may have had but a very subordinate part to play in their accumulation. With this object in mind, attention may be given first to some extracts from the accounts of certain Tertiary formations in the Rocky Mountain region which have been repeatedly described as fresh-water "lake deposits" in the reports of our western surveys; and further on it may be considered whether many of these deposits are not in reality ancient analogues of the fluviatile deposits in modern piedmont plains.

3. *Accounts of Tertiary Lakes in the Rocky Mountain Region.* — Among the earliest references to Tertiary lakes in the Rocky mountain region are those by Hayden. He wrote: — "I would infer that this great fresh-water lake [White river] must have spread over 150,000 square miles" (Geol. Surv. Terr., 1st Ann. Rep. (1867), 58). "With the commencement of the Tertiary was ushered in the dawn of the great lake period of the West. The evidence seems to point to the conclusion that from the dawn of the Tertiary period, even up to the commencement of the present, there was a continuous series of fresh-water lakes all over the continent west of the Mississippi river. . . . The earliest of these great lakes marked the commencement of the Tertiary period, and seems to have covered a very large portion of the American continent west of the Mississippi, from the Arctic sea to the Isthmus of Darien. . . . Every year, as the limits of my explorations are extended in any direction, I find evidences of what appear to be separate lake basins, covering greater or less areas" (Ibid., 2nd Ann. Rep. (1868), 114, 115).

In a chapter on "The ancient lakes of western America," Newberry discussed "the history of this old lake country, as it is recorded in the alternations of strata which accumulated at the bottoms of its water basins" (Geol. Surv. Terr., 1870 (1871), 333).

Powell says that the bad-land rocks of the Green river basin "are the sediments of a dead lake, and are quite variable in lithologic characteristics. We find thinly laminated shales, hard limestones, . . . crumbling bad-land rocks, and homogenous, heavily bedded sandstones" (Colorado river of the west, 1875, 150). Again, the sedimentary beds, north and south of the Uinta mountains, are described as having been "deposited in waters whose shores were limited by the lower reaches of the range; that is, they [the sedimentary beds] all gave evidence of littoral origin" (Ibid., 166). Incidental reference is made to lakes by the same author when describing certain strata of the Green river basin, in such phrases as "the old shore line," "the old Bitter creek lake," "in this great fresh-water basin," and "sands were accumulating in the bed of the lake" (Geol. Uinta Mountains, 1876, 163–165).

Newton's Geology of the Black Hills, as edited by Gilbert, describes the "bed of gravel" at the base of the White river Tertiary formation as "piles of loose pebbles, having all the appearance of a gravel beach on the sea-shore. Indeed, it is evidently a shore deposit, the remains of the beach of the old fresh-water lake, formed before the waters attained their greatest height and while they were sorting over material brought by rivers from the neighboring Black hills." Further on, it is noted as "worthy of remark that while the deposits of the Cretaceous, from the demolition of which the White river Tertiaries were evidently largely formed, are dark carbonaceous clays or shales, the latter are notable for their light color. This is probably due to the making over of the sediment in shallow water, whereby the carbonaceous matter was oxidized, leaving the accumulation nearly white in color. A similar phenomenon is to be seen in the work of the modern streams. . . . The *rationale* appears to be that the finely divided silt derived from the Cretaceous clays has by constant exposure to the air had its carbonaceous coloring matter oxidized and burnt out" (Geol. of the Black Hills, 188, 189).

An essay by Cope on the "Tertiary Formations of the Central Region of the United States" (Amer. Nat., xvi, 1882, 177–195) is naturally devoted for the most part to paleontological matters, but it contains such statements as the following: — "The general history of the succession of the Tertiary lakes of the interior of the North American continent and their deposits has been developed by the labors of various geologists,

prominent among whom must be mentioned Hayden, Newberry, and King" (177). "Extensive lakes were formed in the depressions of the Laramie and older beds. . . . After an interval of time another series of lakes was formed, which have left their deposits over a wider extent of the continent than have those of any other epoch. These constitute the beds of the Loup fork period" (179).

Many explicit quotations may be made from King's writings. In those here following, the page numbers refer to the first volume of the Fortieth Parallel Survey reports. The Vermillion creek beds in the Green river basin are explained by accumulation in a depression "occupied by an early Eocene lake, whose northern portion corresponded with approximate accuracy to the present drainage-basin of Green river" (359). After a description of localities, the author states that "from the outcrops thus broadly sketched, it is clear that a single lake extended from longitude 106° 30′ to 112°, stretching northward probably over the greater part of the Green river basin and southward to an unknown distance" (374). Reference is later made to the "great lake of the Green river period" (393). King's recapitulation is as follows: — "Tertiary time in the region of the Fortieth parallel is therefore represented by nine lakes: four Eocene lakes which occupied the middle Cordilleras . . . ; two Miocene lakes, one in the province of the Plains, the other in eastern Oregon and western Nevada; and, lastly, the three Pliocene lakes" (457).

The early pages of Marsh's monograph on the Dinocerata abounds in references to Tertiary lakes. The Eocene lake of the Green river basin "remained a lake so long that the deposits formed in it, during Eocene time, reached a vertical thickness of more than a mile. . . . As these [Rocky and Wahsatch] mountain chains were elevated, the inclosed Cretaceous sea, cut off from the ocean, gradually freshened, and formed these extensive lakes, while the surrounding land was covered with a luxuriant tropical vegetation, and with many strange forms of animal life." The Dinocerata "which nearly equalled the elephant in size, roamed in great numbers about the borders of the ancient tropical lake in which many of them were entombed" (U. S. G. S. Monogr., x, 1886, 1, 6).

Dutton states that "The Tertiary system of the Plateau country [of Utah] is lacustrine throughout, with the exception of a few layers near the base of the series, which have yielded estuarine fossils. The widely varying strata were accumulated upon the bottom of a lake of vast dimensions" (Geol. High Plateaus of Utah, 158). The strata here referred to are chiefly marls and hence may be largely lacustrine, but

the detailed sections of the High Plateau Tertiaries by Gilbert and Howell (Wheeler's Survey, iii, 157, 267) show the occurrence of numerous alternations between shales, sandstones, marls, and limestones.

Referring to the Tertiaries of northwestern Colorado, C. A. White says: — "They were deposited in great lakes, the existence, extent, and elevation of which were respectively determined by the varying configuration of the general land surface as elevation and degradation progressed (9th Ann. Rep., U. S. G. S., 695).

Weed makes brief mention of "the lake whose sediments formed the Livingston beds" in the lower Tertiary of Montana; and of the gathering of "lake waters in the subsidence that caused the deposition of the great thickness of sandstones and clays that form the Crazy mountains" (Bull. 105, U. S. G. S., 27).

In Clark's "Correlation of the Eocene Deposits of the United States," attention was not especially directed to conditions of deposition; hence his remarks on this subject may be taken rather as a reflection of general opinion than as a result of direct and independent investigation. They present only conclusions without argument, for example: — "From an open sea of Cretaceous age, in which the life was marine, a gradual change took place to great fresh-water lakes in which the typical Tertiary deposits of the Interior were accumulated. . . . The great fresh-water lakes continued with successively dismissed arêas during the remainder of the Eocene period. With the advent of the Neocene an extensive area was again covered with fresh-water lakes which finally became drained in the orographic movements accompanying the elevation of the Rocky Mountains" (Bull. 83, U. S. G. S., 111, 132).

The Neocene correlation paper by Dall and Harris (Bull. 84, U. S. G. S.) contains many extracts from accounts of the fresh-water Tertiaries of the Rocky mountain region, in which frequent references to great lakes seem to be approvingly quoted. As in the preceding paper, the origin of deposits was not the chief subject of the authors' attention in this publication.

The abundant details concerning the Tertiary formations of Nebraska in Darton's recent report on the "Geology and Water Resources" of the western part of that state (19th Ann. Rep., U. S. G. S.) include mention of local and general unconformities, pebbly beds, cross-bedding, and conglomerate-filled channels. Conditions of origin are hardly touched upon in this report, but two phrases suggest deposition in lakes. A certain soil bed is taken to "indicate that there was here a land surface while the Gering formation was being deposited to the south"

(751); and volcanic ash is said to have been "undoubtedly borne on the winds and deposited in the waters which laid down the several Tertiary formations" (761).

Barbour's account of the Devil's Corkscrew or Dæmonelix (Bull. Geol. Soc. Amer., viii, 305–314) reflects the generally accepted lacustrine origin of the Loup fork beds of Nebraska (Arikaree of Darton, the formation that contains a number of old channels filled with conglomerate) in certain phrases, such as "on the sandbars of this lake" (307), "plants which drifted into the lake" (312), "the inference from the branching is that the seaweeds or rootlets . . . grew downward in the sand, not upward in the water" (309).

4. *Characteristics of Lake Deposits.* — The extracts given above might be greatly multiplied. A review of their sources will show that the explanation of fresh-water strata as lake deposits has been almost universal among the geologists of our western surveys. The deposits are as a rule well stratified; they contain no marine fossils; they frequently preserve an abundant land or fresh-water fauna and flora. Without explicit discussion of the various conditions under which such deposits could be formed, the earlier observers seem to have taken it for granted that all the fresh-water sediments were gathered in ancient lake basins; and the later observers have generally followed the belief of their predecessors. In a word, stratification has been taken to mean deposition *under* water and not merely *by* water. There does not seem to be a single instance, in the accounts of the fresh-water Tertiary formations above referred to, of a deliberate inquiry into the essential characteristics of lacustrine deposits, followed by a comparison between the consequences deduced from the assumed theoretical conditions and the facts determined by observation. In the absence of such an inquiry, it does not seem too much to say that it became habitual to speak of strata bearing fresh-water and land fossils as lake deposits, just as strata bearing marine fossils are habitually spoken of as marine deposits. Under the guidance of this habit of interpretation, it was no more worth while to enter into a deliberate inquiry as to the origin of the so-called lake deposits of Tertiary age than into an inquiry as to the origin of the accepted marine deposits of earlier ages.

We may now turn to a theoretical consideration of lake deposits, without attempting to present anything more than a brief outline of their inferred characteristics. It will not be necessary here to consider small lakes, for those inferred to exist in the Rocky mountain region were scores or hundred of miles in extent; and for the moment, shallow

lakes need not be borne in mind, as their deposits will be discussed further on. The present paragraph deals only with the deposits of large and comparatively deep lakes. Such deposits are of two kinds, marginal and central. The marginal deposits may be relatively coarse, but as such they can extend but little distance from the shore line: the marginal strata of subaerial origin should be more nearly horizontal than those of subaqueous origin. The central deposits are shown by studies of existing lakes to be of very fine texture, such as clays, marls, or very fine sands. The stratification of these fine sediments must be very even, with few variations in texture or composition. The movements of the waters of large lakes, either in waves or currents, do not suffice to sweep pebbles out to deep water; hence conglomerates and pebbly sandstones with inclined and cross-bedded layers must be limited to a narrow belt around the lake margin. It can hardly be imagined that the sediments deposited on the floor of a large lake should contain frequent alternations of finer and coarser beds, such as clays and sands; but it may be inferred that the gradual filling of such a lake would allow the encroachment of the later marginal beds upon the earlier central ones; and thus a relatively thin cover of coarse and variable deposits might come to overlie a heavy body of fine and uniform deposits.

If deformation or climatic change should cause repeated variations in the area and depth of a large lake, a complicated series of lacustrine, fluviatile, and subaerial deposits might result; but this will not be further discussed for the present, as the reports referred to above seldom explicitly recognize variations of area and depth, excepting such as occur at the times of separation of successive formations to which different names are given. The manner of mention of the water body in which each formation was believed to have been deposited implies clearly enough that it was thought to be a single, large, continuous lake.

If we now turn to the deposits of large shallow lakes, they are found to be more variable in composition, texture, and structure; for the waves may stir up the materials of the bottom and the currents may shift the materials from place to place; but conglomerates need not be expected to occur among them except close to the shore line. Large shallow lakes cannot, however, be of great importance geologically, for they must be rare and short-lived: rare, because their production depends on the accidental concurrence of unrelated conditions; namely, the crustal deformation of a flat region by a small and nearly uniform amount over a large area; short-lived, because their preservation de-

pends on the accidental compensation of several imperfectly related processes; namely, marginal and central deposition, marginal and central deformation, and lowering of level by erosion at the outlet, or in interior basins by evaporation. It may be pointed out that the preservation of open fluviatile plains during the slow deformation of the floor on which they are accumulating does not involve the balance of conditions or processes so little related as in the case of extensive shallow lakes; for the rate of fluviatile deposition responds most delicately to any deformation of the fluviatile plain. If slow local depression occurs, the rate of aggradation increases and the swinging rivers build up the depressed area about as fast as it sinks. If slow elevation occurs, the swinging rivers tend either to degrade the uplifted area, or to concentrate their deposits on the districts that are not uplifted and thus maintain a generally even surface.

If a shallow lake of large extent should happen to be formed, it would probably soon change by depression to a deep lake or to an arm of the sea; or by elevation, marginal deposition, climatic change, and erosion of outlet to a land surface. Hence the deposits of shallow lakes are likely to be followed either by deep lacustrine deposits or by marine deposits, each recognizable as such; or by fluviatile and other subaerial deposits, particularly around the margin of their basin. The converse of these statements does not seem to hold true; for an open fluviatile plain is more likely to maintain itself as such than a shallow lake is to persist as a broad and thin sheet of water. The deposits of a fluviatile plain are therefore not likely to be associated with those lakes, unless in interior basins.

If a review is now made of the descriptions of the so-called lacustrine formations in the Rocky mountain region, frequent mention will be found of strata that are strikingly unlike those which might be expected from the observation of existing large lakes and from the reasonable extension of principles based on such observations; but before giving examples of this kind, it should be remarked on the other hand that some of the deposits are entirely consistent with a lacustrine origin. For example, King reports that there are even-bedded "paper shales" of very fine texture and with numerous fossil fish in the Green river basin, "giving general evidence of accumulation in still, rather deep water" (40 Par. Surv., i, 447). Russell writes regarding the basin of Lake John Day in the northwest: "Before the Columbia lava was broken and tilted . . . its surface over the whole of central Washington and probably far into Idaho and Oregon, was covered by the waters of a

great lake" in which "the accumulation of fine sediment . . . went on with but slight changes for a sufficient length of time for more than a thousand feet of evenly bedded strata to be laid down one above another" (Bull. 108, U. S. G. S., 22, 23).

It is evident from such examples as these that certain western Tertiary deposits have a well characterized lacustrine facies: but it is also evident that just in so far as Tertiary lakes are inferred from the occurrence of fine and uniform sediments, they are excluded by the occurrence of coarse and variable sediments. It must be concluded that the lakes, whose quiet waters permitted the accumulation of fine-textured, thin-bedded shales, had disappeared when the deposition of cross-bedded conglomerates began. It is possible that some variation of lacustrine conditions may have been tacitly assumed by the writers of the survey reports. It may have been taken for granted that subordinate variations of shore line and depth were produced by orographic movements during the existence of each great Tertiary lake, sufficient to have caused slight changes in the bottom deposits, but not sufficient to have produced significant unconformities in the accumulated strata; or it may have been intended that some small share of the deposits were laid down outside of the margin or above the level of the lake waters; but it would be going beyond the spirit as well as beyond the letter of the reports above quoted to give a considerable value to deposits of subaerial origin, resulting from alternations of land and lake conditions, in any of the western Tertiary formations. When a student reads these reports, he will without question conclude that their authors regarded subaerial deposits as of negligible volume because no mention is made of them, and that the formations are essentially lacustrine because continual mention is made of deposition in large lakes.

Reference will be made again to fine-textured deposits on a later page; attention being now turned to special examples of coarse-textured and variable strata such as are repeatedly described in the accounts of our western "lake deposits."

5. *The Vermillion Creek Beds of Wyoming.* — Many authors might be quoted to show how frequently various kinds of deposits in addition to those of fine texture and even bedding occur in formations that are described as lacustrine; but in this section extracts will be made only from King's account of the Vermillion creek (lower Eocene) beds in the Green river basin, enclosed page numbers again referring to the first volume of the Fortieth Parallel Survey reports. The strata that are found at some distance from the inferred "shore-line of the lake," and

therefore within what may be called the central area of the basin are "coarse red sandstones, interbedded with more or less clays and arenaceous marls of pinkish and creamy colors" (361), "easily eroded red clay and sandy beds" (361), "thin, reddish, flaggy sandstones . . . underlaid by whitish clays" (364), "sandstones and calcareous shales, with slight seams of lignite and several thin beds of a limestone" (365), "dark-drab and gray gravelly sandstones" (367), "several bird-bones from a coarse, gritty, buff sandstone" (367). Near the border of the basin, "conglomerates become more and more important, until directly north of the upper cañon of Weber river the mountain wall is composed of excessively coarse conglomerate between 3,000 and 4,000 feet thick. It is almost structureless, and lines of stratification can rarely be perceived. The blocks of which the conglomerate is chiefly formed range from the size of a pea to masses with a weight of several tons. . . . The rapidity with which these conglomerates grow finer in advancing from the shore along the Uinta is very conspicuous" (369). Sections here exposed in certain canyons "display the graduation of the material from the coarse conglomerate immediately in contact with the older rocks out toward the north, until . . . they have become fine-grained, sandy beds, devoid of pebbles" (370). Near Echo city are presented "3,800 feet of strata, chiefly of these Indian-red sandstones, containing toward the upper limit gray shale-beds, with occasional sheets of fine conglomerate" (371). "West of Concrete plateau there is an enormous development of red sandstones and clays, with prominent belts of conglomerate, the whole increasing in coarseness of sediment as it approaches the Uinta on the south and the Wahsatch on the west. Here is an area about sixty miles from north to south by fifty miles from east to west, which is essentially a plateau of Vermillion creek beds, in general approximately horizontal, but in the vicinity of the Wahsatch rising to 14°" (372). "The thickest exposures of the Vermillion creek series are in the immediate vicinity of the Wahsatch . . . where is exposed not less than 4,000 feet. The most characteristic section . . . is made up of a heavy, gritty series at the base, . . . characterized by . . . red sandstones and clays. . . . The middle members are of finer material and are more intercalated with clays, while the upper part of the series . . . is made up of striped and banded sandstones" (375). "The entire Vermillion creek series . . . was made up of sandstones and intercalated clays, with more or less conglomerates near the old shores of the lake" (380).

It seems perfectly clear from the context that all this formation was regarded as having been deposited *within* the lake waters, on the lake

side and not on the land side of the shore line, below the water level and not above it. Not even the coarse conglomerates are described as the superaqueous or subaerial parts of marginal deltas; no mention is made of the gradual encroachment of marginal deposits upon the area earlier occupied by lake waters. Whatever qualifying ideas the author may have held on these points, they do not appear in his descriptions, and no student would gather them from his text. Yet it is rather in explicitness and detail of statement than in interpretation that this report differs from many others.

6. *The Arapahoe and Denver Formations of Colorado.* — It was not perhaps unnatural, at a time when little attention had been given to the importance of subaerial deposits, that geologists should fall into the habit of regarding all non-marine formations as lacustrine. To-day there is more reason for critical discrimination, and several extracts given further on will show that some geologists have been led to new interpretations of the origin of certain western fresh water Tertiary formations. It is not improbable that other than a lacustrine origin would be attributed to many of these formations, or to many parts of them, if they were now seen for the first time. There are indeed some indications that an unpublished, perhaps unconscious change of opinion has to some extent taken place on this subject, similar to that by which many of the geologists of Great Britain have been transformed from supporters of the theory of marine abrasion to that of subaerial degradation in the production of peneplains. No one would suppose by reading British geological essays of recent years that the British geologists of to-day had very largely given up Ramsay's theory concerning plains of marine denudation, and substituted therefor the theory of subaerial degradation, as advocated by Sir A. Geikie; yet conversation with a number of them last year convinced me that such was commonly the case. Similarly, it may be that our western Tertiary deposits are no longer regarded as exclusively lacustrine by a certain number of American geologists who, although they have published nothing to indicate a change of opinion, may have come by more or less unconscious revision of theories to recognize the great accumulative work that various subaerial processes can have accomplished in Tertiary time. But the change of opinion cannot be universal, for some of the extracts given above from the accounts of our western Tertiaries are from reports of recent years, and one of the recent monographs of the U. S. Geological Survey shows that some of our most experienced geologists still follow the interpretation of earlier years in referring even coarse-textured

fresh-water deposits to lakes, without any published discussion of other possibilities.

The following extracts from the monograph on the "Geology of the Denver Basin in Colorado," above referred to, gives a fair idea of the emphasis that there is placed upon the lacustrine origin of the Arapahoe and Denver formations; all the page references here made being to Monograph XXVII. of the U. S. Geological Survey. "After an erosion of the Laramie beds . . . a considerable fresh-water lake [Arapahoe] was formed and sedimentation again set in. What the exact area of this lake was it is not possible now to determine; its extent was undoubtedly considerably larger than that covered by its beds at the present day, especially to the northward" (31). "The movement which caused the drainage of the [Arapahoe] lake . . . was succeeded after a considerable lapse of time by a depression sufficient to allow of the formation of a second [Denver] lake. . . . The nature of the depression which produced such lakes without admitting marine waters . . . is not readily conceivable" (32). "The beds deposited in the Denver lake reached a thickness of over 1,400 feet along the flanks of the mountains, but were probably somewhat thinner toward the middle of the basin" (33). Certain deposits are referred to as having been laid down near the shore line, but always as if on the lake side of it; for example, "some exposures of Denver strata which clearly show the immediate proximity of the old shore-line" (183); ". . . materials might have been derived from the eastern shores" (201). Several contemporaneous lava flows are said to have been "poured out upon the surface of the sea-bottom" (34). One of these is "the basaltic sheet of Table mountain which was poured out upon the floor of the shallow Denver sea" (161; see also 291, 292); not that direct proof is given of the presence of standing water into which the flows advanced, but that the presence of standing water is involved in the theory of the lacustrine origin of the underlying strata, even though some of them are conglomerates. One of the most significant observations bearing on the conditions of deposition is likely to pass unnoticed by many readers, because it is given only an inconspicuous place in the description of details: — "The presence of considerable tree stumps in erect position with roots in mud layers and broken trunks in sand or gravel, shows that the water was shallow or even that low-land masses alternated with shallow seas. Probably the latter was the case" (168). Nevertheless, the alternations of low-land and shallow water here suggested are elsewhere unmentioned, the usual terms for the area of deposition being "the sea," "the lake."

The materials of the Arapahoe and Denver formations seldom suggest typical lake deposits. "The lower 50 to 200 feet [of the Arapahoe formation] were conglomerates, the upper 400 to 600 feet arenaceous clays" (31). "In passing eastward . . . the conglomerates are gradually replaced by sandstones" (153). "The lower 400 feet of the [Denver] series are composed entirely of eruptive débris; above this point Archean and sedimentary débris are found in small but increasing proportion, and above 900 feet the material derived from . . . Archean rocks is largely predominant" (33). The débris here referred to is elsewhere described as largely conglomeratic near the mountains; on advancing over the Plains, the sediments become finer, but still contain plentiful coarse sands and occasional pebbles, with numerous alternations between fine conglomerate, grits, sandstones, and clays (180, 193, 195).

Repeated instances are given of structures that are much more suggestive of fluviatile than of lacustrine origin. "That the Denver beds were deposited in shallow waters is shown by the frequent cross bedding observable both in sandstone and conglomerate" (33). In the foot-hills, "the sandy parts of the bed develop in places to wedge-shaped masses exhibiting in their relations to each other and to the conglomerate a very marked cross-bedding" (163). "The coarser-grained beds show cross-bedding" (165). Describing a local clay deposit occurring as a break in a conglomerate layer, it is remarked: "Probably the conglomerate succeeding it was deposited in turbulent waters" (177). "The study of the conglomerate series made it evident that fine-grained beds of local development might occur at almost any horizon" (177). On the Plains at ten or twenty miles from the "shore line," special mention is made of "the irregular unconformable contact so frequently seen to exist between a conglomerate or grit layer above and a clay or shale below. . . . Often the unconformability is very marked. . . . The changes in conditions of sedimentation which give rise to such stratigraphical relations of consecutive beds were, however, common in both Denver and Arapahoe epochs. Fine sediments were often disturbed and locally removed at the beginning of periods of rapid deposition of coarser materials" (180, 181).

The fossils, both of plants and animals, give no clear suggestion of a lacustrine origin. "Plant remains and standing tree stumps . . . abound at certain horizons" (33). "The only animal remains yet found in the Arapahoe beds are the bones of vertebrates of new and remarkable types. These occur in the conglomerate along the foot-hills and in the basal sandstones and overlying clays beneath the prairies. In

the conglomerate but few have been found, and these are more or less worn; in the clays they are abundant and their articulation, edges, and muscular insertions are sharp and clearly defined. . . . They are found at all horizons in the formation, and occur buried in the clays or sandstones or partially weathered out upon the surface" (154). "Fossil wood, leaves, and stems are abundant" (169) in certain strata of South Table mountain. Within the limits of the city of Denver "there was formerly a very good outcrop of Denver sandstones and clays, with cross-bedding structure, and full of plant remains in certain layers. Here, too, occurs a thin local seam of coal. . . . In these same strata Mr. T. W. Stanton found some molluscan remains, associated with plants, and a small but perfect crocodile tooth" (193). The fossil mollusca seem to be of fluviatile rather than of lacustrine types.

Nowhere in this report or elsewhere have I been able to find any discussion of the share that fluviatile processes may have had in the origin of the formations, otherwise so elaborately described. Hills has suggested that some of the materials may have been brought from the South park region which "then as now, drained into the Denver basin," thus implying river action in the collection of land waste; but he does not directly discuss the condition of deposition, although the context indicates that he accepted the prevalent theory of a lacustrine origin (Proc. Colorado Sci. Soc., iii, 1890, 393–394). Yet to my reading the record of observations on nearly every page of the Monograph suggests that a fluviatile origin is at least as probable if not more probable than a lacustrine. Conglomerates near the mountains, pebbles and sands alternating with clays on the plains, cross-bedding and local unconformities, standing tree stumps and fossils of large land animals are in my reading all witnesses to rivers rather than to lakes.

7. *Lacustrine and Fluviatile Quaternary Deposits.* — The body of scientific opinion above quoted regarding the interpretation of our western fresh-water Tertiary formations as lake deposits stands in marked contrast to another body of opinion that might be adduced regarding the origin of the Quaternary basin deposits of the same region. The Quaternary deposits that are interpreted as lacustrine are clays and marls, with the addition of the strictly marginal gravels and sands near the shore lines. Mere wedges of gravel between clay and marl beds in the Bonneville basin, wedges that are trifling in volume when compared to many Tertiary conglomerates that have been described as lacustrine, are interpreted by Gilbert as indicating a reduction of Lake Bonneville "so far as to bring subaerial agencies locally into play,"

(Monogr. I., U. S. G. S., 193). Beds of cross-bedded gravel and sand, associated with sandy loam, occur between a lower and a higher marl in the Lahontan basin: of these Russell says: "the remarkable similarity of the middle member of the Lahontan section, as exposed in certain localities, to the . . . deposit formed by meandering streams, leads us to refer its origin with considerable confidence to similar causes" (Monogr. XI., U. S. G. S., 129). Indeed the whole theory of the variations of Quaternary climate in the Great Basin depends on a subaerial origin of certain gravel and sand deposits which are in many ways similar to deposits that have been repeatedly described as lacustrine in accounts of Tertiary formations.

8. *Continental Deposits.* — It was during a western excursion with Professor Penck of Vienna in the summer of 1897 that a possible or probable non-lacustrine origin of many of our western fresh-water Tertiaries was first clearly presented to me. Since then, I have had opportunity of seeing something of the great fluviatile plain of the Po, and of recalling what I had long before seen of similar plains in California and in northern India, as well as of reviewing several essays that bear on the general problem here considered; and the problem has thus come to have an importance that warrants the present review and summary.

Penck's views on this subject may be found in his "Morphologie der Erdoberfläche" (ii, 24–36), where he discusses the occurrence of deposits formed on subaerial plains in the older geological systems. Recognizing that non-marine formations may result under the action of various subaerial agents as well as within lakes, he suggests the name, *continental*, to include all such formations, leaving the discrimination of particular deposits to further study. Penck's term deserves acceptance among geologists, as an aid in the general consideration that it seems desirable to give to the problem of our western Tertiaries; they might be called "continental" in order to avoid implication of either lacustrine or fluviatile origin. Yet as far as the published descriptions of these deposits afford evidence of their detailed structure, it appears to me probable that streams and rivers have had more than lakes or winds to do with their formation, and hence that "fluviatile" might often to advantage replace "lacustrine" in describing them.

9. *Fluviatile Deposits.* — It is perhaps because so much has been written regarding the erosive power of rivers that their constructive powers have been too little considered; but their capacity to aggrade a sinking area deserves as careful examination as their capacity to degrade a rising area. When acting as aggrading agents, they spread out broad

sheets of gravels, sands, or clays, the coarser sediments frequently showing cross-bedding and local unconformities, the finer sediments generally possessing an even stratification. The area over which such deposits may accumulate is shown by existing fluviatile plains to rival that of the western Tertiary deposits. In a region of considerable precipitation, with a background of mountains from which abundant waste is shed to lowlands in the foreground where the rivers have free discharge to the sea, the activity of fluviatile aggradation is often equal to the average activity of the deforming forces that tend to cause marine submergence or to produce broad lake basins. A slight acceleration of littoral depression might cause submergence, or a rapid local warping might produce a lake; a pause in these movements would allow the rivers to convert the sea border or the lake into a fluviatile plain again. The preponderance of one condition or the other might be determined by the proportion of fine, evenly stratified layers (if such deposits are necessarily marine or lacustrine, and out of the reach of river action) to variable strata with cross-bedding and local unconformities in the resulting deposits, as well as by a study of the fossils that they contain.

The capacity of rivers to form extensive deposits of fine texture and even stratification seems in particular to be underrated. It is true that a torrential river, gathering coarse detritus and exposed to heavy floods in its headwaters among lofty mountains, may carry cobbles and pebbles many miles forward upon a piedmont fluviatile plain. The artificial enclosure of its channel by dikes to prevent overflow probably increases the distance to which pebbles can be carried, as on the plain of the Po; but if the river is free to spread upon an aggrading surface, the pebbles would be sooner laid down. In arid regions the coarse piedmont deposits assume great importance, as is more fully stated below. On the other hand, rivers of moderate size, rising in uplands of moderate height, may contribute chiefly very fine and well stratified sands and clays to the plains that they aggrade. This will be especially true if their headwaters drain regions of deep soils, such as occur on slightly elevated peneplains; or of weak strata, such as are found in basin deposits of earlier date. At times of high water and overflow, rivers of this kind will spread layers of fine silt far and wide over their plains, and the repetition of this process must lead to the formation of thick deposits, fine in texture and even in structure, with little admixture of coarser sands and pebbles. Ripple marks, foot-prints, and raindrops may be preserved in the sediments of shallow flood-plain lagoons, and mud-cracks may form as the lagoons are dried up. The plains of the Po and of the Ganges, and the great fan of

the Hwang-ho are very largely composed of fine sediments; the proportion of fine to coarse materials in the extensive deposits of these rivers seems to be greater than it is in many of the so-called lake beds of the West.

The surface of many extensive fluviatile plains seems level as far as the eye can reach. This level surface is the best obtainable index of the evenness of structure that must prevail both in the strata already laid down beneath the plain, and in those yet to be deposited upon the plain. In the absence of special studies on the degree of continuity of river deposits, it cannot now be said how far a single stratum or a group of strata, marked by recognizable peculiarities of texture or color, may extend; but it may be urged that mere continuity of even bedded deposits, such as is reported in our western Tertiaries, even if occurring over areas of many square miles, should not alone be taken as conclusive evidence of lacustrine origin. Some other criterion than continuity is needed to distinguish fluviatile from lacustrine deposits of fine texture. No other feature seems so likely to serve this need as the filled channels and lateral unconformities that must occur, albeit rarely, even in the finer fluviatile deposits. The occasional presence of these distinguishing structures might readily escape notice in beds whose continuity has been traced only by observations of colored strata, such as are visible at a distance on the barren slopes of arid regions.

10. *The Indo-Gangetic Fluviatile Plain.* — The alluvial deposits of the Indo-Gangetic plain stretch over hundreds and hundreds of miles. They are well described in the Manual of the Geology of India by Medlicott and Blanford (or in the second edition by Oldham, 1893, 427–458), where references are given to original articles for further details. Gravels and conglomerates are abundant near the sloping borders of the plain, while the prevailing material of the central area is some form of clay, more or less sandy, with subordinate deposits of sand, gravel, and conglomerates; but pebbles are scarce at greater distances than twenty or thirty miles from the enclosing hills. Borings show the deposit to be hundreds of feet, and at one point more than a thousand feet in depth, with no trace of marine fossils; and from this it is inferred that depression accompanied accumulation. Organic remains are not common, but shells of river and marsh molluscs are occasionally found, and calcareous material is not lacking; the latter is frequently gathered in concretionary nodules; it sometimes forms compact beds of earthy limestone. The clays bordering the Jumna, as well as the calcareous shoals of this river, have yielded remains of a variety of vertebrates, including elephant, hippopota-

mus, ox, horse, antelope, crocodile, and various fish. The borings yield pebbles, sands, and clays, with peat and wood, and remains of terrestrial mammals, fluviatile reptiles, and fresh-water molluscs.

Still more pertinent to the present discussion is the account given of the inclined strata of the Siwálik (Tertiary) formation in the Himalayan foot-hills (Ibid., 356–368). "The lower portion of the system is characterized by a great thickness of fine grained grey, micaceous, pepper and salt sandstone, interbedded with clay bands near its lower portion, while the upper part of the system is composed of soft earthy clays, undistinguishable from the alluvium of the plains, . . . and coarse conglomerates of well rounded pebbles and boulders" (356). These strata are much tilted; their thickness is estimated at 14,000 or 15,000 feet. The vertebrate fauna of the Siwálik formation is well known to paleontologists. "The earlier observers regarded this great series of beds as having been deposited in a sea, a supposition which is sufficiently disproved by the complete absence of any marine organisms, and by the occurrence of the remains of fresh water molluscs, fishes, and tortoises. It is hardly possible that they could have been deposited in a fresh water lake, for it is not conceivable that a fresh water lake extending the whole length of the Himálayas could have existed. Moreover, the fresh water organisms whose remains have been found are all such as inhabit streams, and not lakes. The very close resemblance between the upper Siwálik beds and the recent deposits of the Gangetic plain leaves little room for doubt that the Siwálik beds were deposited subaerially by streams and rivers" (358). While it does not seem necessary to deny the possibility of conceiving the existence of a lake all along the base of the Himalayas, the necessity for believing in such a lake seems to be removed by the striking resemblance between the upturned Siwálik strata and those of the Indo-Gangetic plain.

11. *Fluviatile Deposits of the Great Plains.* — In view of these various considerations and examples bearing on the competence of rivers to form extensive stratified deposits of fine as well as of coarse texture, there seems little room for doubt that some part of the fresh-water Tertiary formations that stretch forward from the Rocky mountains across the open slope of the Great Plains may be of fluviatile and not lacustrine origin. The first observer to reach this conclusion was Gilbert, whose views are to be found in a report on underground water in eastern Colorado (17th Ann. Rep., U. S. G. S., 553–601). He ascribes the Tertiary strata that unconformably overlie the Cretaceous of the Plains chiefly to river action, but partly to transportation by wind and to deposition in

lakes. The change from the erosion of the Cretaceous floor to the deposition of the Tertiary cover "was brought about by some modification of conditions which is not yet clearly understood. Perhaps the plains region was depressed at the west, and the slopes thus rendered so gentle that the streams could no longer carry off the detritus which came from the mountains, and it was deposited on the way. Perhaps a barrier was lifted at the east, so that the base level stood higher. Whatever the cause, the streams . . . filled their channels so that their beds lay higher than the neighboring country . . . and they thus came to flow in succession over all parts of the plains and to distribute their deposit widely, so that the whole plain in the district here described was covered by sands and gravels brought from the canyons and valleys of the Rocky mountains. The chief material is coarse sand . . . in irregular beds with much oblique lamination. In the sand are occasional pebbles and . . . beds of gravel. . . . At the northeast, . . . clays, marls, and other fine-grained beds alternate with the sand in the lower part of the formation, and these are probably continuations of the lake deposits observed in Kansas" (575, 576).

Haworth goes even further than Gilbert in excluding lacustrine conditions in his discussion of the "Origin and Mode of Formation of the Tertiary" in Kansas (Univ'y Geol. Surv. Kansas, ii. 1897, 281–284). After quoting extracts from Gilbert's report, this author says: "The relative positions of the gravel, sand, and clay of the Tertiary over the whole of Kansas . . . correspond much better to river deposits than to lake deposits. The irregularity of formation succession, the limited lateral extent of the beds of gravel, clay and sand, the frequent steepness of the cross-bedding planes, all correspond to river deposits, but are not characteristic of lake deposits. . . . It is quite possible that during Tertiary time, in which there were so many changes in the velocity of the water carrying the sediments, lesser local lakes and lagoons and swamps and marshes may have existed in different places and for varying lengths of time. But when we consider the Kansas Tertiary as a whole and yet in detail, it must be admitted that the materials themselves have many indications of river deposits and a very few of lake deposits" (283).

12. *Fluviatile Basin Deposits.* — Broad plains frequently occupy basin-like areas enclosed by mountains. Streams flow from the enclosing slopes to the central depression, whence the united waters find escape through a gorge in the bordering highlands. Such plains frequently give the impression of having been once occupied by a lake. The plain of Hungary is an admirable example of this kind, yet there is much

probability that its strata have been deposited for the most part by aggrading rivers. The sediments to-day laid down by the Theiss and other rivers that wander over the central parts of the plain are of very fine texture. Borings show that similar sediments underlie the surface to depths of 100 to 200 meters. As described by Penck, these deposits consist of a complex of fine sand and clay layers whose sections, disclosed in neighboring bore holes, are so unlike that deposition in a lake is held to be impossible. The plain of the middle Rhine is a longitudinal *graben*, enclosed by uplands through which the river has cut its narrow gorge north of Bingen; but here again the evidence of borings is taken by Penck to be decidedly in favor of a fluviatile origin for the deposits (Morph. der Erdoberfl., ii, 15). In both cases it must be concluded that the deformation by which the basins were produced was so slow that the production of lakes was prevented by deposition on the depressed floor and by erosion on the rising rim. An older example of this kind is offered by the fresh-water Molasse of Switzerland, flanking the Alps on the north, and now uplifted, tilted, and eroded. It is often referred to as a lacustrine formation, and its marls may well justify such a reference; but its heavy sandstones and conglomerates, such as are now upturned in the marginal range of which the Righi is a member, give strong suggestion of fluviatile origin. The resemblance of the Swiss Molasse to the Siwálik beds of northern India has been pointed out by Medlicott (Quart. Journ. Geol. Soc., 1868, 45, 46).

The subrecent deposits of Kashmir, Nepal, and Hundes, all basins within the Himalayas, are of special interest in the present connection, for they have been described as lake deposits, although now referred chiefly to fluviatile agencies (Manual Geol. of India, 2nd edition, 422). Their dimensions are comparable to those of some of our western Tertiary basins. They frequently contain fine deposits in the more central areas, and these may have been laid down in temporary lakes; but in Kashmir the repeated occurrence of beds of shingle and sand alternating with thin layers of lignite point to a subaerial origin; and while the central deposits of Hundes are "a fine homogeneous clay with but little gravel in it, . . . there is nothing to show that the whole [series of layers] . . . might not be of subaerial origin, as it is almost certain that the bulk of them might have been." The clays and gravels now dissected to a depth of 3,000 feet contain mammalian remains, including the rhinoceros, ox, horse, hyena, sheep, and goat.

13. *Rocky Mountain Basin Deposits.* — The resemblance is so strong between several of the basin deposits here described and the Ter-

tiary formations of the Green river and other Rocky mountain basins, that a fluviatile origin for many of the latter becomes probable; but re-examination in the field with special attention to discriminating structures will be necessary before definite conclusions can be announced. It is also probable that the basins produced by the Pliocene deformation of the previously denuded Rocky mountains of Montana may have been at least during part of their existence occupied by fluviatile plains as well as by lakes. Hayden referred to them only as lakes: — "These . . . broad valleys [of the Missouri headwaters in Montana] have all been lake-basins during the last portion of the Tertiary period," and on another page he says: — "The great valleys . . . during the latter Tertiary period were the basins of fresh-water lakes, so that we have everywhere the white and yellowish-white sands, marls, clays, sandstones, and pudding-stones of the Pliocene lake deposits passing up into the Quaternary or local drift" (Geol. Surv. Terr., 1871 (1872), 147, 141).

The same comment may be made regarding deposits of the basins of South park and San Luis valley, Colorado, which were described as lacustrine by Stevenson (Wheeler's Survey, iii, 453, 461).

14. *Deposits in Arid Basins.* — In regions of drier climate, such as interior continental basins, calcareous, saline, and alkaline matter may slowly accumulate along with detritus of finer or coarser texture in the central depression, while conglomerates, gravels, and sands would gather to greater thickness in laterally confluent fans around the mountain borders. The importance of marginal deposits of this kind, both recent and Tertiary, is attested by the following quotation from Powell, who says: "I think that many geologists would ascribe this [Bishop mountain] conglomerate to the action of ice, but throughout all that portion of the Rocky mountain region which I have studied, I have so frequently found gravels and conglomerates of subaerial origin, and have in so many cases found reason to change my opinion concerning them, often having attributed a drift-like deposit to glacial action, and afterward on further study abandoned the theory, being able to demonstrate its subaerial origin, and witnessing on every hand the accumulation of such gravels in valleys, and over plains where mountains rise to higher altitudes on either side, and having in many cases actually seen cliffs breaking down and the gravels rolling out on the floods of a storm, I am not willing to disregard explanations so obvious and so certain for an extraordinary and more violent hypothesis. . . . Nor need the thickness and extent of this Bishop mountain conglomerate serve to weaken this explanation, for the sub-aerial gravels in the valleys between the ranges in the Basin province

are of equal and often of greater development. Whenever a low plain, valley, or basin is for a comparatively long period but little elevated above the base level of erosion, and during this time mountains and hills stand about the lowlands, there must be a great accumulation of drift, and where the highlands are areas of progressive elevation and the lowlands areas of progressive subsidence this accumulation may continue indefinitely" (Geol. Uinta Mountains, 170, 171).

Dutton's Report on the High Plateaus of Utah may be quoted to the same end: "There is another class of conglomerates which claims our special attention. These are of alluvial origin, formed, not beneath the surface of the sea nor of lakes, but on the land itself. They do not seem to have received from investigators all the attention and study which they merit. . . . Throughout great portions of the Rocky mountain region they are accumulating to-day upon a grand scale and have accumulated very extensively in the past." After describing the transporting action of torrents in mountains, and their depositing action at the mountain base, the same author says: "The formation thus built up is an 'alluvial cone.' . . . The slopes near the circumference usually lie between 1° and 2°; those near the apex between 2° and $3\frac{1}{2}$°. The lengths of the radii of the bases often exceed 3 miles, sometimes exceed 4 miles, and seldom fall below 2 miles. . . . So nearly together are the gateways along the mountain and plateau flanks, each having its own alluvial cone, that the cones are confluent laterally; giving rise to a continuous marginal belt . . . consisting of alluvial slopes which are sensibly nearly uniform. . . . Our surprise is often great at finding the cone wonderfully well stratified." Examples are then given of heavy Tertiary conglomerates which are ascribed to an alluvial origin, although they are "about as well stratified as the average of those which are attributed to sub-aqueous deposition" (Geol. of the High Plateaus, 1880, 219–223).

The occurrence of calcareous materials other than pebbles in fluviatile and subaerial deposits is seldom discussed. Marls and limestones, even if impure, are taken as evidence of marine or lacustrine conditions. Yet earthy limestones are explicitly recognized among the strata of the fluviatile plain of northern India, as above noted, and calcareous material may be deposited as a cement in the piedmont wash of an arid region. Concerning the latter, Hill writes as follows: — "Throughout the limestone regions of the hot climates of America a superficial crust of white-lime material is found, called tepetate. Sometimes it is comparatively free from foreign material, or occurs as the matrix or cement of conglomerates. This is a concentrate of the lime which has been

dissolved from the surface, transported in solution by the torrential streams, and redeposited through evaporation. . . . Tepetate is forming great incrustations around the margins of the bolson plains of northern Mexico" (18th Ann. Rep., U. S. G. S., 256).

Many other references might be made to the importance of the subaerial deposits or "wash" at the base of sub-arid mountains, for such deposits are well known in Utah, Nevada, and southern California, as well as in more distant parts of the world (see Hilgard, Cienegas of Southern California, Bull. Geol. Soc. Amer., iii, 127; Manual Geol. of India, 2nd edition, 417, 418; Blanford, Superficial Deposits in the Valleys and Deserts of Central Persia, Quart. Journ. Geol. Soc., xxix, 1873, 493), but a return to the reports of Fortieth Parallel Survey will suffice. Here one may find abundant testimony to the competence of subaerial processes to form extensive deposits flanking mountain ranges, but attention is given almost exclusively to the coarse, unstratified deposits that are formed by storm floods near the mouths of mountain valleys. For example: — "The interior valleys of the Cordilleras, from California eastward to the Wahsatch range, are all filled to a varying depth with subaerial Quaternary accumulations. . . . In each one of these [Great Basin] depressions is a considerable covering of angular and sub-rounded Quaternary gravel, always of an evidently local character, directly to be traced to the flanking mountain ranges. Its coarseness varies from large bowlders, weighing many tons, to fine gravel, sands, and clay. Except where it has been rearranged in the now extinct Quaternary lakes, it is altogether an unstratified deposit, brought down by the rush of floods from the flanks and cañons of the mountains" (40th Par. Surv., i, 460). The sands and clays that are gradually washed far forward from the piedmont fans of coarse gravels and conglomerates can hardly have been in mind when describing these subaerial deposits as "altogether unstratified." I cannot find that any cross-reference was made from the account of these heavy unstratified conglomerates to the description of the almost structureless conglomerates, between 3,000 and 4,000 feet thick, already quoted from the description of the Vermillion creek lake deposits (380). It is possible that a re-examination of certain "lacustrine" conglomerates in the Rocky mountain Tertiaries might lead to their explanation as arid subaerial deposits.

The central deposits of arid interior basins may be as fine as the marginal deposits are coarse. The playas or mud plains of Nevada, as described by Russell, and the plains around Lob Nor in the central

basin of Asia, as described by Sven Hedin, are composed of excessively fine materials, yet they are rather of fluviatile than of lacustrine origin in the ordinary sense of these words. If a shallow lake occurs in the lowest part of interior basins of this character, it occupies but a small part of the entire depression; it is variable in position, shifting to a new site as it is driven about by growing deltas; it is still more variable in volume, changing with the weather, the season, the century, and the climatic cycle. Only in epochs of moist climate does a playa lake reach dimensions comparable to those attributed to the Tertiary lakes of the Rocky mountain region; yet in dry as well as moist epochs, fine sediments gather in the basin, aggrading its floor. The manner in which the fine mud of playas is distributed when the very shallow water is agitated by wind is said to prevent the production of well defined stratification. Ancient playa deposits would therefore be prevailingly of a massive structure, instead of being finely laminated like typical lake beds; and they would be associated with wedges of coarser deposits that were washed forward on the basin floor by intermittent streams.

15. *Æolian Deposits.* — Wind-borne dust and showers of volcanic ashes are both of importance as possible contributors to subaerial deposits, particularly in regions where the streams are aggrading the surface, and where running water is incompetent to remove the aerial sediments. The recognition of wind-borne dust is still a matter of uncertainty, or at least a subject of disagreement. Volcanic materials are in recent years generally detected by the aid of the microscope. Matthew has recently called attention to the importance of wind deposits in an article entitled, "Is the White River Tertiary an Æolian Formation?" (Amer. Nat. xxxiii, 1899, 403–408). This author begins by saying that the Loup fork beds have been "shown to be largely a flood-plain deposit" (403), and closes with a statement that the Rocky mountain Eocene is "probably a mixture of lake and fluviatile sediment — what proportion of each would not be easy to determine" (408). He objects to the origin of the White river clays in a lake because of the size of the lake required, and because of the absence of an eastern barrier and of shore lines; furthermore, he states that the clays are not well stratified; they contain land mammals in abundance, but they preserve no plants, no fish, and no aquatic reptiles or invertebrates. While the included sandstones are thought to be river-laid, the clays are said to be better accounted for by æolian action, such as is now going on in the production of loess on the open grassy surface of the subarid Plains. This article is of especial interest, not only from its

critical quality, but also because it is concerned with a fine-textured formation which has been referred to a lacustrine origin with more confidence than almost any other in the Rocky mountain region.

16. *Summary.* — The object of this paper is to promote consideration rather than to announce conclusions. The author's leaning towards the explanation of parts of our western Tertiary formations as fluviatile rather than as lacustrine deposits is not to be concealed, but he would prefer to leave the decision of the points here mooted to those who have a larger personal knowledge of the Rocky mountain region than he has. Observations recorded by western explorers and geologists are in no case disputed; descriptions of observed structures are accepted as if they were first-hand facts; but the origin attributed to the observed structures is not always accepted, because it is thought that other interpretations than those offered by the observers are in some cases to be preferred. This essay is therefore not concerned with the direct observation of facts in the Rocky mountain region, but with the theoretical discussion of recorded observations, a discussion in which any one may reasonably take part, whether he has visited the region under consideration or not, provided that the facts of structure are well observed and described by those who have been there.

It is in no spirit of antagonism, but simply from interest in a theoretical problem that expression is here given to an opinion in a matter of interpretation different from that adopted by the authors whose observations are quoted; an opinion which it seems advisable to express freely in order to bring the discussion of the problem to the attention of geologists interested in this aspect of their science.

The points in discussion seem to be in the main these: — Lake waters may receive materials of various kinds from their shores and from the rivers running into them; and the materials thus gathered, coarse and fine, will be deposited in stratified arrangement near the border and over the floor of the lake. Their volume will depend on the rate, area, and period of accumulation. River basins may also, under certain conditions, receive in their lower portions more material than can be carried forward and discharged into the sea; or interior basins not containing lakes may be gradually aggraded by the materials washed in by streams from the enclosing highlands: here again the materials may be coarse and fine; they may have a stratified arrangement, the area of deposition may be small or large; and the volume of the deposits will depend on the rate, area, and period of accumulation.

Recognizing these possibilities, assured by observation in various parts

of the world to-day, how can the products of similar conditions in the past be recognized? In both cases, the deposits are stratified; in both cases, the deposits may include fine as well as coarse materials; in both cases, the area of deposition may be large as well as small; in both cases, the thickness of deposits may be great as well as light; in both cases, the strata may bear ripple-marks, mud-cracks, cross-bedding, and other indications of small and variable water depth. With all these similarities, it would not be remarkable if a lake deposit were sometimes called a river deposit, or if a river deposit were mistaken for a lake deposit; for the safe discrimination of the two classes of deposits must depend on their differences, not on their resemblances. While the marginal sediments of a lake may be coarse, the body of the central sediments must be fine and uniform. The marginal parts of a fluviatile deposit may also be coarser than the forward parts, but the latter may be characterized by frequent variations of texture and structure, and occasionally by filled channels and lateral uncomformities. The origin of the western fresh-water Tertiary formations should be considered with all these items in mind, and with an equal hospitality to the fluviatile and to the lacustrine theory.

In whatever way the discussion on this subject may end, it may be noted a considerable body of geological opinion will follow its decision. The lacustrine origin of the fresh-water Tertiary formations has had an acceptance so general and undisputed that it has for some years held a place in the geological history of the Rocky mountain region as an established doctrine. Many examples of this might be given. Dutton writes: — "I know of no more impressive and surprising fact in western geology than the well attested observation that most of that [High Plateau] area has been covered by fresh-water lakes. . . . The marvel is not in the fact that here and there we find the vestiges of a great lake, but that we find those vestiges everywhere. The whole region, with the exception of the mountain platforms and pre-existing mainlands, has passed through this lacustrine stage" (Monogr. II., U. S. G. S., 216). The occurrence of numerous Tertiary lakes is made the basis of inferences concerning Tertiary climate by the same author: — "We know that the Miocene climate of the west was moist and subtropical. This is indicated by the great extent of fresh-water lakes in some portions of the west, their abundant vegetable remains, and the exuberance of land life" (Ibid., 223); but fluviatile plains do not imply a moist climate. A low stand of the western part of the continent during part of Tertiary time as inferred by the same geologist from the long endurance of

lacustrine deposition: — "A considerable number of large lakes being formed, the next process was the desiccation of these lakes and the evolution of river systems. So long as the region occupied a low altitude this process, we may infer, would be very protracted. Before a large lake can be drained its outlet must be cut down. But several causes in the present instance would combine to render this action very slow and feeble. The elevation being small, the declivity and consequent corrasive power at the outlet must be correspondingly small. Moreover, the waters issuing from a large lake contain little or no sediment. . . . Corrasion by clear water is an exceedingly slow process" (Ibid., 218). On the other hand, fluviatile and subaerial deposits may accumulate at considerable altitudes above sea level in interior basins.

The preservation of numerous vertebrate fossils was explained by Marsh as "probably, without exception, due to their entombment beneath the waters of the great fresh-water lakes which existed in this [Colorado] region during Mesozoic and Cenozoic time" (U. S. G. S., Monogr. XXVII., 525). From the time when Warren first called attention to the inclined position of the Pliocene strata of the Plains, their attitude has been taken to prove a post-Pliocene elevation of the Rocky mountain system by all writers who have considered the subject. If the Pliocene of the Plains is fluviatile instead of lacustrine, a much smaller elevation may be demanded.

The Tertiary lakes of the Rocky mountain district have become stock subjects of geological teaching, as the subject is represented by the text-books generally in use, and it is here that my own interest in the matter is especially aroused. Dana, Leconte, Scott, and Tarr all assert the existence of Tertiary lakes without qualification; they give no indication that a large share of the so-called lacustrine formations may really be of fluviatile or other subaerial origin. Similar statements are naturally made by the standard European text-books, such as those by Geikie, Lapparent, and Credner, who naturally adopt the lacustrine origin of our western Tertiaries without demur. The older generation of geologists, who had a first-hand acquaintance with the facts, may have interpreted "lacustrine" very liberally, including therein a considerable share of marginal subaerial deposits; but the brief and direct statements of the text-books leave the coming generation of geologists no option in the matter; they will accept the completely lacustrine origin of all the deposits so-called. The probability or possibility of fluviatile origin is not given a chance to gain a hold in the

mind, for its place is taken by an opinion already established in favor of lacustrine origin. In all efforts to visualize the Tertiary geography of the Rocky mountain region, our students are now led to imagine broad sheets of level water surface, scores or hundreds of miles across, and well deserving the name of "seas" often given to them in various reports; and the long slopes of subaerial plains to which an important place may come to be given now receive very scanty consideration.